An FPGA-based Design Approach for Microsatellites Telemetry Subsystem

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***Abstract*—The Tele-command and Telemetry (TT&C) subsystems are one of the vital components in satellites. Commanding, managing and data sampling from different sections of the satellite are performed through the TT&C subsystem. The telemetry and Tele-command parts of this subsystem could be implemented cooperatively with or separately from each other. Based on the satellite requirements, its mission and orbital lifetime and cost various approaches may be used in order to implement this subsystem. Furthermore, nowadays, the development of satellite subsystems based on commercial devices because of their low cost and accessibility is more attractive. However, their endurance for harsh space environment remains as a severe challenge. The Field Programmable Gate Arrays (FPGAs), one of the best-developed commercial devices, are most successfully option in this application field. Nevertheless, the system designing methodology and the reliability of the implemented system on FPGAs remain as two major concerns. In this paper designing method and implementation result of Telemetry subsystem on field programmable gate array (FPGA) is presented. The implemented subsystem successfully passed environmental test according to ECSS standard. Furthermore, flight data confirm the feasibility of the presented FPGA based design methodology.**

***Index Terms*— Satellite; TT&C Subsystem; Field Programmable Gate Array (FPGA); Flight Data.**

I. Introduction

Remote sensing satellites provide continuous measurements of the earth and its environment and take accurate pictures of the earth's surface that are used for scientific investigations about changes occurring around the world such as crops, water, and other terrestrial resources [1]. Nowadays, the main design criteria for satellites is low cost and fault tolerance, which have been achieved by using Commercial Off the Shelf (COTS) components [2]. Advances in the semiconductor industry have been leading to high-density COTS chips by technology scaling, reduced voltage operation, and higher frequencies; one of the most famous devices in this field is SRAM-based Field-Programmable Gate Arrays (FPGAs) [3]. FPGAs are programmable logic devices, which allow the user to specify the function to be performed. There are many available resources within an FPGA to perform various logic functions. Therefore, the use of FPGAs in space and military applications is increased. The growing need for mission requirements and demanding for low-cost designs, especially for Low Earth Orbit (LEO) satellites, conduct the designers to use FPGAs in their plans.

In this paper, we aim to present a designing approach based on FPGA to realize telemetry subsystem, as a case study, for a sample LEO satellite (Figure 1). Our satellite includes various subsystems such as Telecommand and Telemetry (TT&C), Power, Attitude Determination and Control Subsystem (ADCS), image payload (IP) and so on which are linked to provide the earth observation mission (Figure 2).

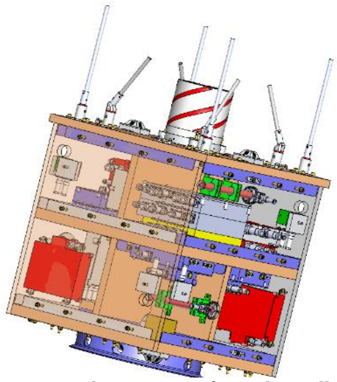

Figure 1: the structure of sample satellite

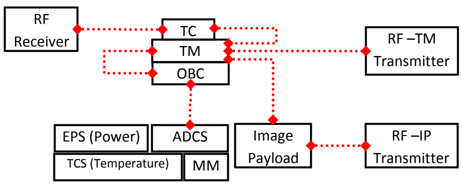

Figure 2: data pass among sample satellite subsystems

As we know, each section has a predefined role in a satellite system. In the power subsystem, solar panels in combination with batteries are used to generate, store, control, and distribute a constant supply of electrical power throughout the satellite. The communication subsystems use transmitters, receivers, or transponders to handle all transmit and receive communication functions. The Attitude Determination and Control Subsystem (ADCS) allows the antennas and camera to remain pointed correctly to the earth. The thermal control subsystem regulates the temperature of the satellite components. For earth observation mission, the aim of the Image Payload (IP) is to take high-resolution pictures from earth. The Telecommand receives remote control commands from the earth control stations and performs equipment-operating adjustments. The telemetry section, as the case study in this paper, monitors the on-board equipment's operation and transmits equipment's operating data to the earth control stations. In general, the telemetry is the process by which an object's characteristics are measured, and the results transmitted to a control station where they are displayed, recorded, and analyzed. Based on data analysis, some commands may be transmitted to the satellite. Therefore, the telemetry data have a critical role, especially for a ground-based control aims of satellites [4][5][6].

The remainder of this paper is organized in the following way: First, we briefly survey the related works. Then, we summarize the conceptual description of the Telemetry subsystem in the case study satellite that we will use in the remainder of the paper. Section IV describes the detailed design and implementation results on FPGA. Before use in the satellite, we have subjected the product to standard terrestrial tests according to the ECSS standard that is mentioned in Section V. Section VI represents the on-flight data that are received from the satellite. Finally, the on-flight data have provided, and Section VII concludes the paper

II. RELATED WORKS

The Tracking, Telemetry and Command (TT&C) system is a vital subsystem of the spacecraft that has been investigated in some previous works. in [7] describes the conceptual design of a distributed telemetry and telecommand system, which is based on processors, to be employed on the SUNSAT microsatellite. Telemetry and command subsystem for a Mexican experimental microsatellite are described in [8]. According to [8], the computation part is a microcontroller that is planned to operate in a catastrophic case in which the onboard main and redundant computers fail. A TT&C system for microsatellite has been introduced in [9][10], which is based on a Cortex microcontroller (µC) electronic. Also, in [10] a TT&C subsystem is introduced for Libyan imaging mini-satellite (LibyaSat-1). However, in this reference, the RF section has been investigated and TT&C electronics are partially neglected. The command and data management system (CDMS) of the Philae, which include the telemetry and telecommand function, also contains 13 FPGA, however, is mainly based on microprocessor [11]. Another work in [5], describe the TT&C subsystem for a microsatellite in which the telecommand part consists of four microprocessors, and two microprocessors for the telemetry part. In this Ref., the FPGAs are used for I/O expansion aims. Also, the telemetry concept has been realized in previous literature. However, this paper provides a new design method completely based on FPGA. The FPGA based approach offers the reconfigurability platforms which are attractive for new satellite designs [12]. None of the previous works are not entirely based on FPGA. This paper proposes a complete FPGA based design that all of the data gathering, managing, framing, coding, and transmitting processes are implemented on a single FPGA. Therefore, we expect the hardware complexity is decreased. The proposed method, which has hierarchy topology, is relied on interrupt request mechanism and single task per moment. This means that the proposed design approach supports only a single task in each period of the time, although it is able to support variety tasks. For multi-mission aims, ones can use a multi-sectional PROM. Moreover, in the proposed method, the sampling or data acquisition mission, the major and most complex task of telemetry, is based on interrupt request from low-level modules in the hierarchy. The following sections describe the requirements, details, evaluations, and implementation results of the proposed designing method for sample telemetry subsystem based on FPGA.

III. CONCEPTUAL DESIGN OF TELEMETRY SUBSYSTEM

Telemetry provides important information about the status of the satellite by monitoring its system components, such as health signals, temperature variations, voltage and current levels. Telemetry data are transmitted from the satellite through a Radio Frequency (RF) channel data link to the ground station, where the information can be received, decoded, and analyzed. Once the telemetry is analyzed it can serve many useful purposes. It can be used as a diagnostic tool, as informative data which can be used in redesigning and building newer satellites, and as a monitoring instrument to see if a status should be changed on-board the satellite from the ground station through the uplink [13]. As mentioned, telemetry is a process by which an object's characteristics are measured, and the results transmitted to a ground control station or other subsystems of the satellite. This process involves gathering measurements (such as magnetic field, voltage, current, and temperature) into a format which can be transmitted as a single data stream through radio frequency subsystem. Pulse Code Modulation (PCM) is today's preferred telemetry format due to the fact that its accuracy is high and thousands of measurands can be acquired along with digital data from multiple sources.

The presented Telemetry subsystem, beyond the data acquisition, executes the different task in various modes which are defined through the ground station and telecommand section. Generally, telecommand determines telemetry's mode with three digital lines. The operational modes of telemetry include: Broad Casting (BC), Play Back (PB), on-time Sampling, and Recording. The following gives a brief statement of the main tasks of telemetry in each mode. In Broad-Casting (BC) mode, a specific message ("YA MAHDI *"), which is saved in the Read Only Memory (ROM), is transmitted to the Radio Frequency (RF) subsystem when the telemetry mode is set in broadcasting mode. In Play-Back mode, to guarantee the accuracy of each decoded and unframed command package, the received commands are played back to the ground station. In this case, the command packages are sent to the telemetry unit. Then, these packages are framed, coded and carried to the transmitter. In Sampling mode, the data gathering is the main task of the telemetry subsystem. Data are framed according to IRIG standard, coded, and transformed to the ground station. In the following, major considerations of each mode are demonstrated. These considerations include the data package, frame length, synchronization words.

The specific number of words includes the synchronization words, mode or frame counter, and reserved bytes, are inserted beside each other and creates packages. The data packages of Broad-Casting mode are illustrated in the next section. Beside synchronization and mode words, the ASCII code of desirable message (i.e., " YA MAHDI *") are infixed in the package. The rest bytes of package considered as reserve words for future developments. Similarly, the package of Playback mode is illustrated in the next section. In sampling mode, the volume of data which must be handled is vast, and therefore the use of single package isn't reasonable. For this reason, the IRIG framing standard is used in sampling mode. The implemented frame is a fixed format of IRGI standard. Fixed formats do not have changes during transmission with regard to the frame structure, word length or location, commutation sequence, sample interval, or measurement list. According to this standard, Pulse code modulation (PCM) data are transmitted as a serial bit stream of binary-coded time-division multiplexed words. The PCM data shall be formatted into fixed length frames. Frames shall contain a fixed number of equal duration bit intervals. As stated by this standard, the minor frame is defined as the data structure in time sequence from the beginning of a minor frame synchronization pattern to the beginning of the next minor frame synchronization pattern. Furthermore, a major frame contains the number of minor frames required to include one sample of every parameter in the format [14].

The maximum length of the implemented minor frame is equal 256 words. Therefore this frame is considered in class I. Each minor frame contains the frame synchronization pattern, frame counter or telemetry mode, and data words. The frame synchronization consists of a fixed digital word with 32 bits. The frame counter and telemetry mode provide a natural binary count corresponding to the minor frame number; also distinguish the package of different modes. Major frame length is defined as minor frame length (N words) multiplied by the number of minor frames (Z) in the major frame. The number of minor frames in our design is equal to 16 frames.

In order to simplify the system design on the FPGA, the minor frame for the Sampling mode has been used as the basis of other modes. Consequently, the length of other packages and available reserved words in these packages depends on the minor frame length. As mentioned previously, the different packages of the telemetry modes are distinguished by the mode/counter word.

If we assume that the t parameter represents the period of time between two minor frames. Therefore, to accomplish major frame in the sampling mode, the desired data are classified based on this parameter. The measurands that require higher sampling frequency, as compared with t, are repeated multiple times per minor frame. Similarly, a group of measurands that occurs at a slower data rate than t, are broke into small pieces and are presented in the multiple minor frames. According to IRIG-106 standard, these cases are called Super-commutation and Sub-commutation respectively[14].

IV. DESIGNING AND IMPLEMENTING

In order to provide the requirements of a satellite system, the telemetry subsystem is designed in a hierarchical structure with two levels (Figure 3). In the lower level, for each external connection or measurand, a module is allocated. All of the low level modules are managed by the top-level module. In the following sections, the structure and details of these modules are considered.

A. Low-Level Modules

As illustrated in Figure 4 low-level modules are set as the interface for on-board electronic, image payload, telecommand subsystems. Moreover, the temperature, voltage, and current data gathering through the signal conditioner units are accomplished by these interfaces. Major tasks of these modules include data gathering, managing, and transmitting to the highest level of hierarchy in a specific format. The general structure of the low-level modules includes a finite state machine, local RAM, and a multiplexer (Figure 4). The complexity of the finite state machine depends on module duty. After the reset signal of the module is released, data gathering is started. After the data is stored in the local RAM inside the module, the Ready signal is activated. In this condition, if the Enable signal is activated, the content of the local RAM is submitted the high-level module through the multiplexer. All of the low-level modules follow this signaling. Therefore, the top-level of the proposed system is designed based on the interrupt request. The Clock and Reset signals of low-level modules are controlled through the top-level module. Consequently, the sampling rate and timing of each data set are adjusted by the top-level. Following the data transmission from the local RAM to the Major frame according to IRIG-106 framing, the enable signal is de-asserted and therefore the state machine inside the module sends back the Enable signal to "0" level. The state machine waits in this state until it receives a Reset signal. As mentioned before, the Reset signal is applied by the top-level module which completely manages the timing of low-level modules. The structure of the top-level module has presented in the following section.

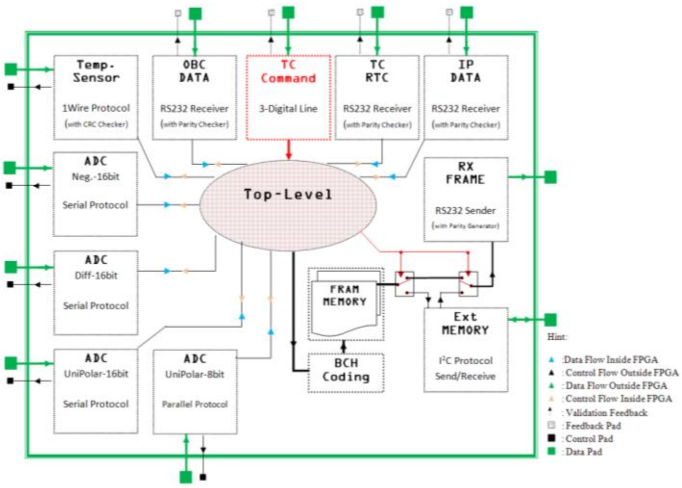

Figure 3: General block diagram of sample telemetry hierarchy

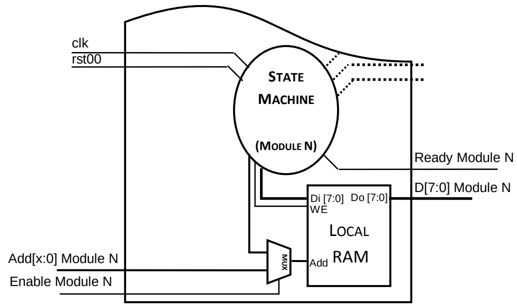

Figure 4: block diagram of low level modules in sample TM

B. Top Level Module

The block diagram of the top-level module is illustrated in Figure 5. As mentioned before, the presented telemetry subsystem supports different modes or tasks include the Sampling mode, the Broad-Casting, and Play-Back which determined through the Telecommand subsystem. According to this block diagram, the top-level module consists of a Major frame memory, a Minor or Inferior frame memory, a Play-Back memory, a Broad-Casting Read Only Memory (ROM), timing generator block, coding and transmitter block, and a specific finite state machine for each mode and so on. The telemetry mode is driven from the telecommand section through three logical signals. In order to prevent conflict between frames, a specific state machine called as Mode-Lock is used. The Mode-Lock state machine, based on the mode signals from telecommand and Inferior frame sending duration (t_{SoIF}), maintains subsystem in one mode at least for one t_{SoIF}.

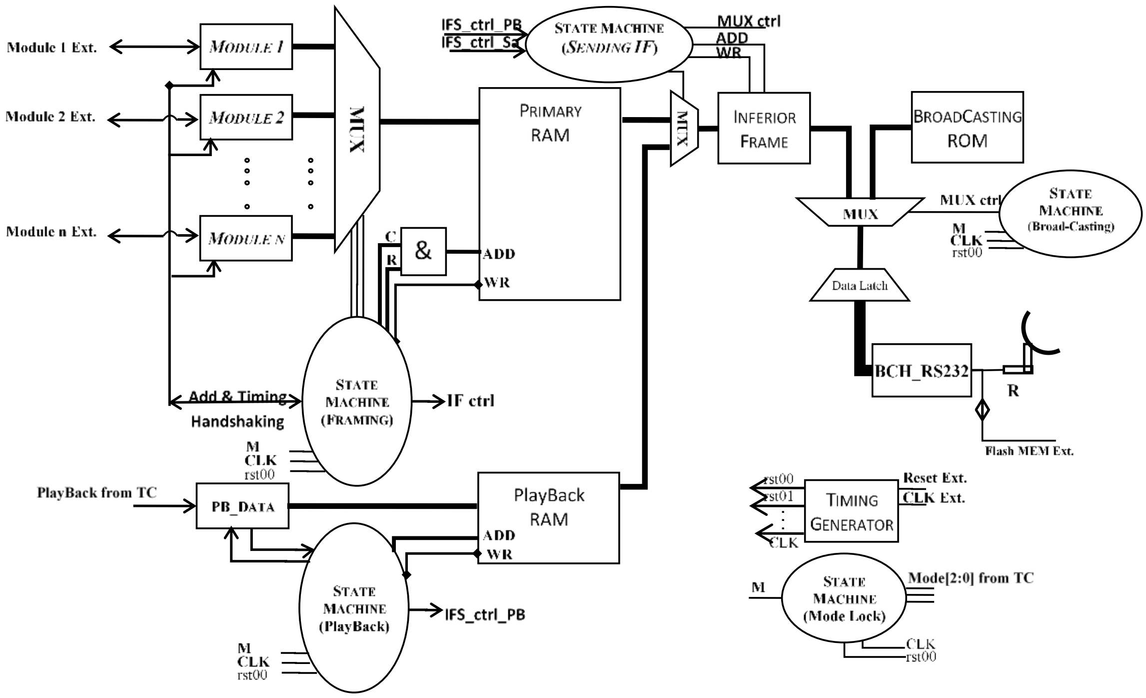

Figure 5: block diagram of top level modules in sampling mode

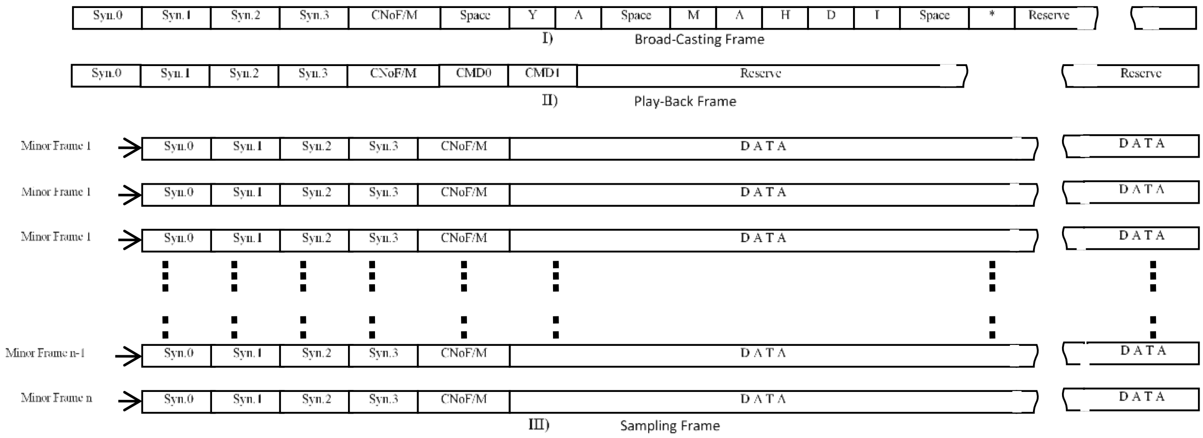

Figure 6: data frames of sample TM in different modes

This state machine ensures the frame integrity before they are handled over the Rf transmitter. The output signal of the Mode-Lock state machine drives other state machines. Consequently, other state machines have appropriate time, at least equal to t_{SoIF}, to manage or transfer data.

In the case of Broad-Casting mode, the broad-casting state machine is activated, and other state machines remain in the idle state. Therefore, the Broad-Casting state machine manages the data pass from the external ROM to the RF transmitter. The signaling in the ROM memory, the coding block, and the RS232 unit are accomplished by this state machine. The default message in the external ROM is according to the package type as illustrated in Figure 6-I. In Play-Back mode, the data packets are received from the telecommand unit and stored in the Play-Back memory through the low-level module, and then a copy of the data is transported to the Inferior frame according to Figure 6-II package. The state machine for sending the Inferior frame is activated. Consequently, the data channel to the transmitter is managed by this state machine. The flow charts of the Play-Back and Inferior frame state machines are illustrated in Figure 7 and Figure 8 respectively. Once a package of data is played back both of state machines go in the idle state. They remain in this condition until a reset signal is received from a timing generator block. Finally, in the Sampling mode, the Framing state machine manages and controls all of the data handling from low-level modules to the transmitter. The data handling involves data gathering, framing, coding and transferring. From the digital system design point of view, the main approach in this mode is based on the interrupt request. The Framing state machine provokes low-level modules to take samples of the measurands according to a predefined schedule which specified by satellite system designers. An interrupt request is sent from each module to the Framing state machine, after their data gathering process accomplished (Figure 9). The lifetime of the components is calculated based on MIL-Hdbk-217 standard. Also, the failure modes, the effects analysis or failure modes effects and criticality analysis (FMEA/FMECA) process, are performed for this subsystem [15]. According to EEE-INST-002 standard [16], this product is suitable for level 3 space programs. The typical mission duration for level 3 programs varies from less than 1 year to 2 years[16]. The maximum total power consumption of the implemented hardware

(Figure 10) is equal to 500mW. All used components basically are in the commercial/industrial grade. Also, the summary of resource requirements on FPGA device is summarized in Table 1

Table 1: summary of implementation results

MODULE	FLIP-FLOPS	LUTS	MAX. FREQ.
1-WIRE	167	193	165.89MHz
IP-LINK	91	221	79.403MHz
OBC-LINK	91	221	79.403MHz
RF-LINK	96	228	121.635MHz
TC-LINK	91	221	79.403MHz
ADC NEG.	60	121	133.101MHz
ADC POS.	87	169	117.940MHz
ADC HIGH RES.	204	391	130.409MHz
ANALOG TEMP.	192	103	134.704MHz
TOP LEVEL	1464	2990	54.734MHz

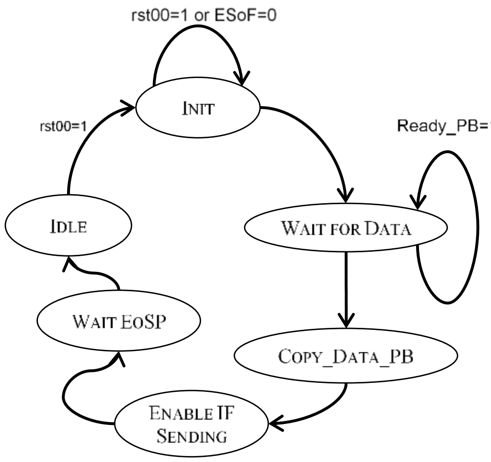

Figure 7: finite state machine of PlayBack Mode

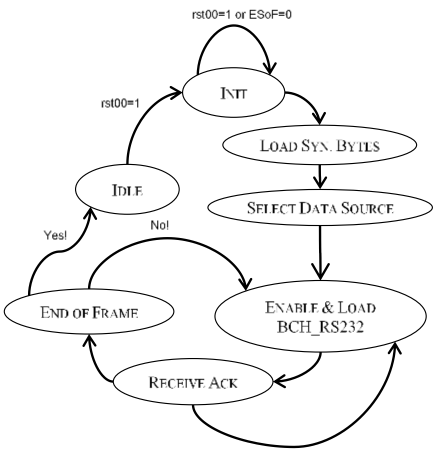

Figure 8: finite state machine of Inferior frame sending

V. TERRESTRIAL FUNCTIONAL AND ENVIRONMENTAL TEST

All predefined functions for the telemetry section are evaluated in the satellite clean room. Moreover, the space-bound scientific instruments are subjected to an extensive ground test before they are launched to ensure a successful launch and a proper on-orbit operation. The vibration environment for space payloads during the launch phase is typically simulated on the ground before the launch. The vibration methods include: the random vibration and sine vibration tests which are subjected to the telemetry equipment. As we know, a properly packaged electronic components are able to tolerate the vibration tests without failure. According to the previous experiences in the IUST satellite research center, the wires, connectors, and solder joints usually are failed before other parts. So, we have provided some special consideration in the printed circuit board and the wiring, according to Ref. [17].

Moreover, our equipment has been subjected to the conventional vacuum and thermal tests. The provided test plan has been adopted from space standards especially ECSS-70-02A and also ECSS-E-10-03A [18]. The test specification has been extracted through the orbital condition of the satellite. The plate and equipment temperature during the thermal vacuum test is depicted in Figure 11 and Figure 12, respectively. In the first cycle, the environment temperature is set in the [-30, 45] interval, while for the other cycles this interval is limited to [-20, 35]. This temperature is the plate temperature, which represents the chamber environment temperature, which is measured through the sensors. While the equipment temperature characterizes the evaluated temperature inside the telemetry board. This board is positioned in the sealed box, so it senses a moderated and postponed temperatures. It is better to mention that, during the thermal test, we have faced with a failure in the tantalum electrolytic capacitor which is located in the power line. We have replaced this commercial grade capacitor with military grade one, and successfully passed the test

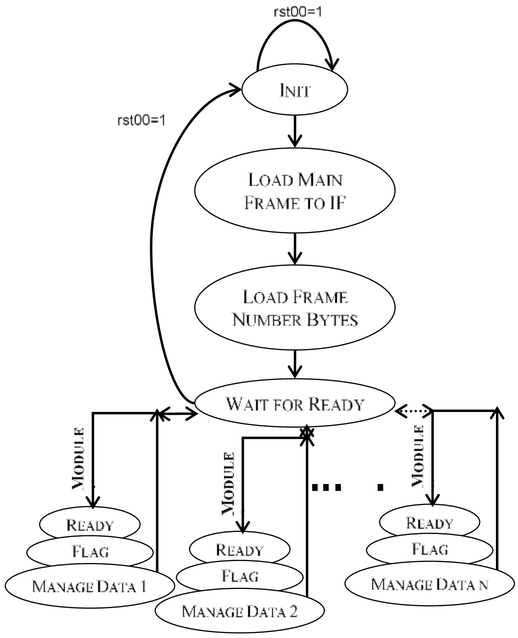

Figure 9: finite state machine of Inferior frame sending

Figure 10: Photo of prototype model of telemetry

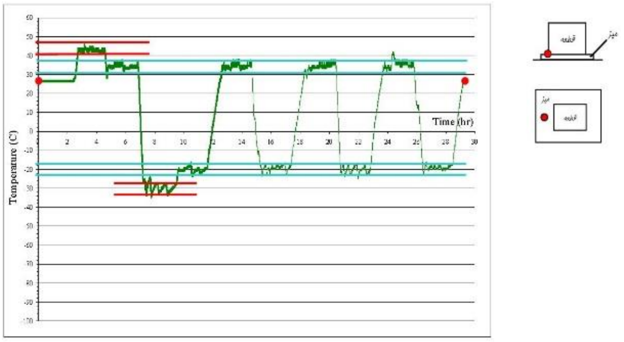

Figure 11: Thermal vacuum test sequence (Plate)

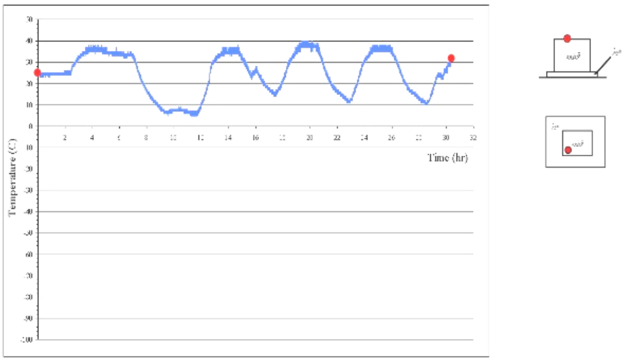

Figure 12: Thermal vacuum test sequence (Equipment)

VI. ON-FLIGHT DATA

Usually, the satellites transmit a data stream to the ground stations that are called mnemonics. These data are used to determine the satellite status and health signals and locate the satellite position. The mnemonics must be analyzed to ensure that the satellite is in a good state, also to assist in resolving any anomalies, and to determine if there are any trends that would indicate a possible future problem. The satellite engineers need assistance to integrate these large volumes of data. The following describes some on-flight mnemonics.

The real-time clock (RTC) of the satellite is placed in the Telecommand section. This section is turned on as soon as the satellite injection into the orbit is completed. Therefore, the satellite time is available for all subsystems and it is sampled through the Telemetry section. Each telemetry frame contains the satellite time, which is transmitted to the ground stations. In Figure 13 a portion of the real-time clock data (second only) is presented. These data refer to the mission time of 24day: 13hour: 57min. As expected, the second is changed in 0 to 60 ranges. None data sections in the diagram are related to the temporal failures in the communication link. Moreover, Figure 14 shows the variation of frame number for telemetry data which are received in the ground stations. As aforementioned, our telemetry frames contain 16 subframes, so this number is varied from 0 to 15. As mentioned, the none data sections of the diagram are associated with the transient failures in the communication link. The maximum and minimum experienced temperatures for several different parts in the satellite are illustrated in Figure 15 to Figure 16. However, these temperatures depend on the satellite seeing local times and execution of telemetry scenarios. Due to the fact that the telemetry scenario is done over the satellite seeing periods. In other word, the data acquisition is not performed for a complete period of a day.

The first DC/DC converter, which feeds the Telecommand section, is always active. Therefore, the reported temperature data from this unit is somewhat greater than other sections. The second DC/DC converter which supplies the Telemetry Transmitter (TTx.) is turned on during the satellite seeing period. It takes a maximum duration of 10 minutes. Consequently, the experienced temperatures of this section are slightly modest. Also, the temperature of the Telemetry box is presented in Figure 17. Due to the fact that, the TM board has limited power and it activated for a short period, so its temperature data are in an appropriate range.

The temperature of the external surface of the satellite is also sampled and depicted in Figure 18. The reported temperature because of the circular movement property of the satellite (spin-stabilization satellite) is reasonable. This temperature is a yardstick of the environment temperature. In order to provide a fixed voltage for critical sections in the satellite during the mission, a series of the battery is placed in the satellite. The appropriate variation range of battery voltages is at 10 to 15 volts, for the cases that the voltage is lower than this range, the required power for transmitter could not be supplied. The batteries are charged by the solar arrays through the charger unit. The minimum and maximum reported voltages of the battery during the mission are shown in Figure 19. The minimum voltages are related to the satellite seeing during the night. The solar cells are arranged in four strings which feed a common voltage bus. According to our satellite configuration, just one string, which has the highest voltage, is switched to the bus. The minimum and maximum reported voltage of the Y-string and bus voltages are presented in Figure 20 and Figure 21. It is necessary to hint that the zero values in the reported data illustrate that data sampling is performed during the night and therefore the string voltage and consequently the bus voltage are zero. We have archived all data for the satellite mission duration. In this paper, we have just illustrated a part of data to validate of design in the flight.

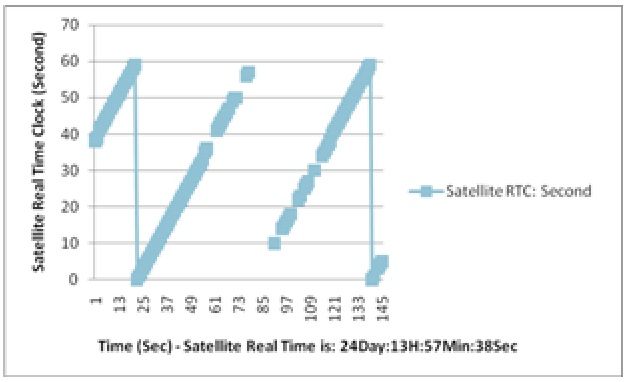

Figure 13: Real Time Clock (RTC) of satellite (Second only)

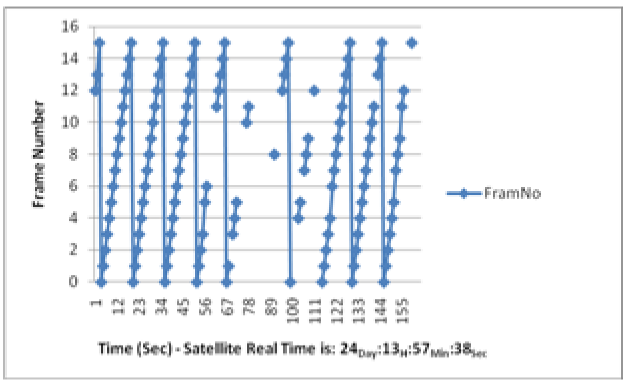

Figure 14: Frame number of the satellite

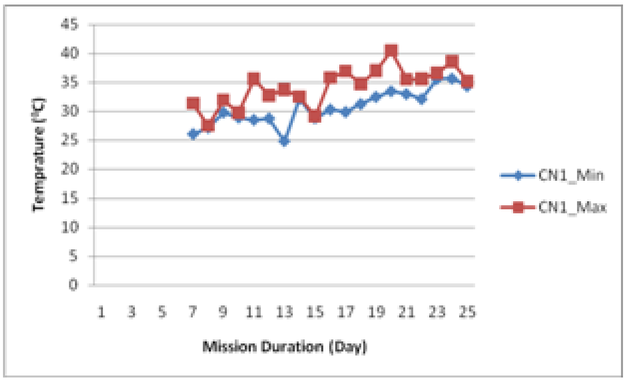

Figure 15: minimum and maximum temperature of first the DC/DC convertor

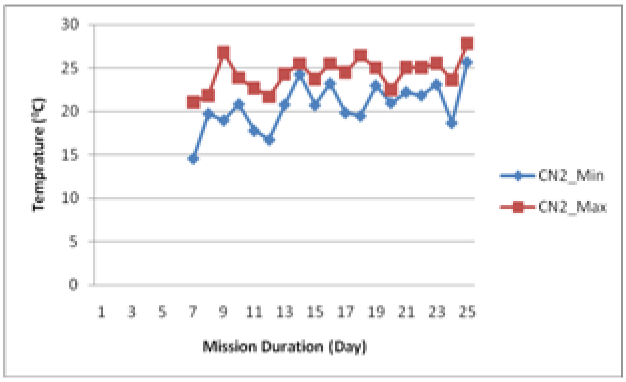

Figure 16: minimum and maximum temperature of the second DC/DC convertor

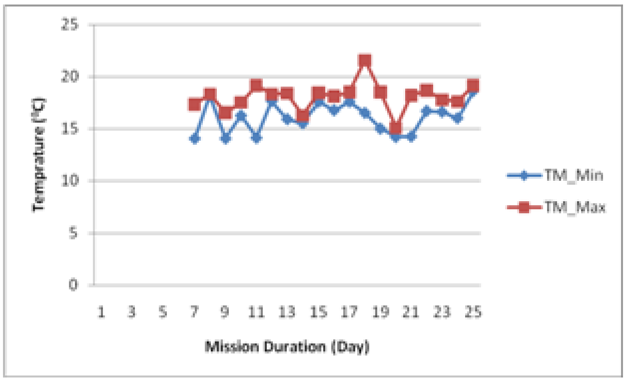

Figure 17: minimum and maximum temperature of Telemetry

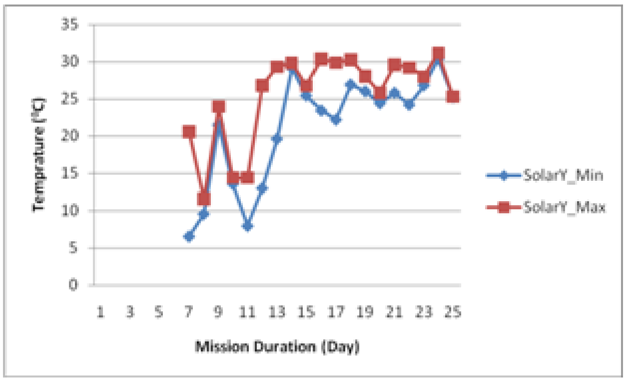

Figure 18: minimum and maximum temperature of solar panel

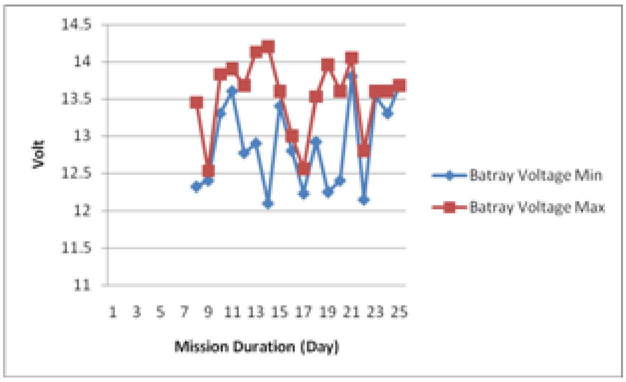

Figure 19: minimum and maximum voltage of satellite battery

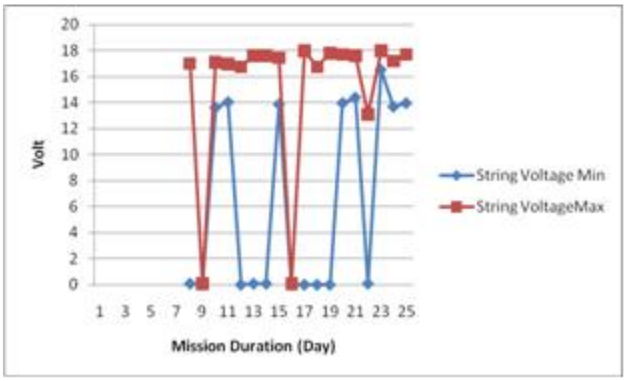

Figure 201: minimum and maximum voltage of the solar panel

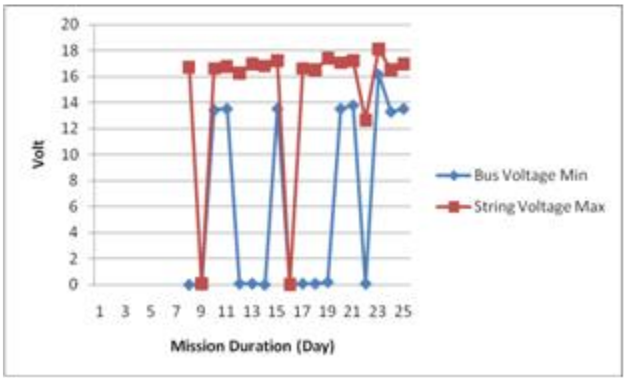

Figure 21: minimum and maximum voltage of satellite bus

VII. Conclusion

This paper has presented a design and implementation of Telemetry subsystem based on field programmable gate arrays in order to use in Microsatellites. The design process which is discussed here has resulted in equipment that is completely based on COTS components. The proposed approach, beyond its conventional mission, is able to be developed to execute different tasks. We have employed the interrupt request mechanism in hierarchy design, so the adding/removing of modules could be completed effortlessly and quickly. The experimental data from satellite flight and the terrestrial environmental tests have verified the suitability of the proposed approach for LEO satellites.

References

[1] Wertz and Larson, "Space Mission Analysis and Design," (third ed.) Space Technology Library, 2011.

[2] D. Del Corso et al., "Architecture of a Small Low-Cost Satellite," *Digital System Design Architectures, Methods and Tools, 2007. DSD 2007. 10th Euromicro Conference on, Lubeck,*2007 pp. 428-431.

[3] R. Omidi and K. Mohammadi, "Hybrid time and hardware redundancy to mitigate SEU effects on SRAM-FPGAs: Case study over the

MicroLAN protocol," *Microelectronics Journal*, Volume 45, Issue 7, pp. 870-879, 2014.

[4] V. V. Aleksandrov, A. D. Belen'Kii, D. I. Bugrov, A. V. Lebedev, S. S. Lemak, and W. F. Guerrero Sanchez, "Telemetry-based estimate of orientation accuracy for the Tat'yana-2 satellite," *Moscow University Mechanics Bulletin*, vol. 66, pp. 72-75, 2011.

[5] J. Liu, H. Zhang, W. Zheng, and L. Yin, "Design of telemetry and telecommand subsystem of a micro-satellite based on industrial-level chips," *International Journal of Circuits, Systems and Signal Processing*, vol. 6, pp. 97-104, 2012.

[6] C. T. Tsai, H. H. Wen, Y. F. Tsai, and J. C. Juang, "Design and implementation of microsatellite telemetry, tracking and command (TT&C) subsystem," *Journal of Aeronautics, Astronautics and Aviation, Series A*, vol. 44, pp. 39-46, 2012.

[7] Jan-Albert Koekemoer, Pieter Bakkes, Sias Mostert, Distributed telemetry & telecommand for future sunsat missions, Acta Astronautica, Volume 44, Issue 7, Pages 531-541, 1999.

[8] E. Pacheco, J. L. Medina, R. Conte and J. Mendieta, "Telemetry and command subsystem for a Mexican experimental microsatellite," *IEEE Proceedings Aerospace Conference, Big Sky, MT*, vol.3, 2001, pp. 3/1159-3/1165,

[9] D. Cinarelli and P. Tortora, "TT&C system for the ALMASat-EO microsatellite platform," *IEEE First AESS European Conference on Satellite Telecommunications (ESTEL)*, Rome, 2012, pp. 1-6.

[10] F. E. M. Tubbal, A. Alkaseh and A. Elarabi, "Telemetry, tracking and command subsystem for LibyaSat-1," *9th International Conference on Telecommunication Systems Services and Applications (TSSA)*, Bandung, 2015, pp. 1-6.

[11] A. Balázs, A. Baksa, H. Bitterlich, I. Hernyes, O. Küchemann, Z. Pálos, J. Rustenbach, W. Schmidt, P. Spányi, J. Sulyán, S. Szalai, L. Várhalmi, "Command and data management system (CDMS) of the Philae lander, Acta Astronautica," vol. 125, August–September, pp. 105-117, 2016.

[12] X. Cao, "Flexible platform based micro-satellite design method, Aerospace Science and Technology," Vol. 53, pp. 162-168, June 2016.

[13] P. C. Haddock, "Telemetry data collection from OSCAR satellites," San Diego, CA, USA, Pages 39-46, 1998.

[14] t. T. G. o. t. R. C. Council, "IRIG-106," in *PULSE CODE MODULATION STANDARDS*, ed, 2011.

[15] E. C. f. S. Standardization(ECSS), "Space product assurance: Failure modes, effects and criticality analysis (FMECA)," ed, 7 September 2001.

[16] K. Sahu, "EEE-INST-002 Instructions for EEE Parts Selection Screening Qualification and Derating," 2008.

[17] ESA-ESTEC Requirements & Standards "Design rules for printed circuit boards," ECSS-Q-ST-70-12C, 14 July 2014.

[18] ESA-ESTEC Requirements & Standards "Thermal vacuum outgassing test for the screening of space materials," ECSS-70-02A, 15 November 2008.